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A RISK MANAGEMENT MODEL PROPOSAL FOR COMPLEX PROJECTS IN TECHNOLOGICAL INNOVATION

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Abstract. *Technological Innovation Projects are usually characterized by great integration among the subsystems that comprise the final product, limited resources available (financial, infrastructure, time and people), restrictive laws and also the need for attainment of new levels of requirements, which is directly responsible for the success of the product. The attainment of such requirements is usually reached by the adaptation of existing technologies or by the incorporation of new ones. In any case, the compliance of all requirements and the successful implementation of the technology are essential for designing a worthwhile product. By this reason, the product development process requires a good monitoring process of physical and financial development. Another key task for the success is to monitoring the development process of critical technologies for the product. This article proposes a model to manage technological risks in projects of high technological innovation focused on monitoring the maturity level of the technologies to be incorporated into the product. This model consists of tools and methods widely used in both academic and business environment namely: concepts of the Project Management Body of Knowledge (PMBOK) for project management, Design Structure Matrix (DSM) for the establishment of inter-relationships among subsystems, concepts of System Engineering to establish the systems and subsystems that compound the product and eventually, Technology Readiness Level (TRL) to measure the maturity level of technology to be added to the product. Simulation of an industrial case study, is presented to demonstrate the applicability of the proposed model.*

Keywords*: Project Management; Systems Engineering; DSM; TRL*

1. INTRODUCTION

Since the essence of technological innovative projects is the transformation of effort and resources into products and processes that incorporate significant competitive through a combination of research and product development, a robust management process is a must, especially when resources are scarce and there is a strong demand for deadlines and requirements compliance.

In a scenario where there is clearly an overlap between the usual product development process (PDP), research and development activities (R&D) where basic and applied research are mixed, major risks are included and risks of delays, cost increase and products that do not fulfill the expected requirements grows considerably.

This makes the technology maturity monitoring process of fundamental importance but it will not, alone, ensure the success of the project, but represents an essential element for predicting problems and helping the assessment of mitigation plans.

2. APPLICATION CONTEXT

A Product Development Process (PDP) can be by itself highly complex when it involves products with multiple systems and subsystems. However this complexity level can be strongly increased when it is incorporated into normal development process, research activities that seek solutions to be integrated into the final result.

This new scenario brings several new challenges beyond the usually faced such as the lack of proficient teams, the supply chain availability, the manufacturing processes capability, local and international polices, legal aspects and so on. This fact means that technological innovative projects are more susceptible to delays, costs increase, final product price growth or even the completely fail of the project. It is known that to avoid all risks one does not have a real scenario in a researching environment. The best option is to focus effort to manage all risks, especially those which are out of control.

The application of off-the-shelf technology, fully maturated, would be the most appropriate solution: however when the objective is to improve a competitive differential it becomes almost essential to handle some new critical technology elements (CTE) for the product in fact to fulfill a certain mandatory requirements.

3. THEORETICAL RECITAL

The concepts described herein will not be presented or argued in detail but rather, at a level that is enough to make clear the proposed method.

3.1. Technological Innovation

The first step to understand the complexity and the peculiarities of technological innovative projects is to look at its definition. The term innovation has received several definitions along the time, such as the Oslo Manual, whose concept has been set as the introduction of a product, service or new process or a significant improvement that differs from others (OECD, 1997). A broader view is given by Schumpeter: technology innovation may be the introduction of a new product, a new production method, the opening of a new market, the conquest of a new supply source or even the establishment of a new industrial organization (Schumpeter, 1982).

In this paper, technological innovation is referred to as the implementation result of coordinated efforts and resources to produce, a new product or process, or a significant improvement to a good, representing a relative advantage against the current status.

3.2. Project Management

According to a classic definition presented in the Project Management Body of Knowledge (PMBOK), Project Management "is the application of knowledge, abilities, tools and techniques into project activities to reach all requirements” defined to the project and to fulfill all needs and expectations of the involved parts related to the project (PMI, 2004. p.nn).

In accordance with the PMI (2004), Project Management consists of the joint application of several management techniques that aims at reaching the goals and objectives posed, through the balance of several variable**s** involved in the process. The usual project variables: (a) Integration: focused in the coordination of the elements of a project; (b) Scope: represented by the delimitation and control of the project’s objectives and goals; (c) Schedule or time’s definition: the sequence and control of the activities; (d) Costs presented by the estimation: budget and financial resources control; (e) Quality reached from the planning: guarantee and control; (f) Human resources obtained from organizational planning and work teams development; (g) Communication summarized by the generation: capture, distribution and storage of information; (h) Risks represented by the identification: analysis and answers to the involved risks; and (i) Acquisitions planning and election of suppliers and merchandises.

3.3. System Engineering

One of the first steps to build a proper product component’s hierarchy analysis and perform a suitable deployment, as showed in Fig.1, is to establish an appropriate nomenclature, terminology and definition to all levels. To this end, this work applies the concepts disseminated by the System Engineering Handbook (INCOSE, 2004) to use in fact a worldwide accepted terminology. The main concepts are:

System – The highest level of a structure. It represents an integrated set of elements, segments and/or subsystems that accomplish a defined objective, such as an air transportation system.

Element or Segment - A major product, service, or facility of the system, e.g., the aircraft element of an air transportation.

Subsystem - An integrated set of assemblies, components, and parts which performs a cleanly and clearly separated functions, involving similar technical skills, or a separate supplier. Examples are an aircraft on-board communication subsystem or an airport control tower as a subsystem of the air transportation system.

Assembly - An integrated set of components and/or subassemblies that comprise a defined part of a subsystem, e.g., the pilot’s radar display console or the fuel injection assembly of the aircraft propulsion subsystem.

In order to reference lower levels of the system hierarchy it can be used other definitions such as Subassembly, Component and Part according to the need of specific product.

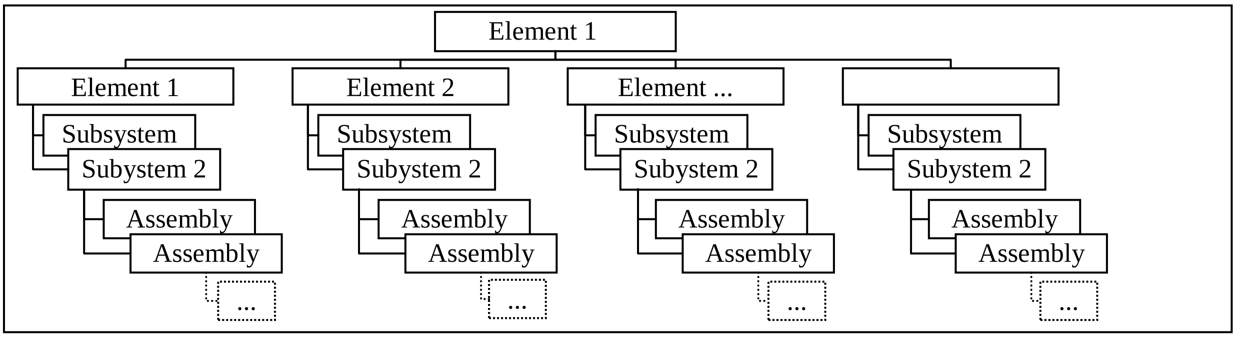


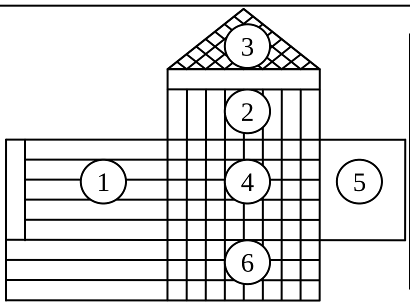
Figure 1: Deployment hierarchy of a system.

3.4. Quality Function Deployment (QFD)

This technique, widely used within the enterprise environment, is a suitable tool to deploy the requirements, as suggested by the System Engineering Handbook (INCOSE, 2004). Its main feature is the ability to translate the voice of the customer into engineering data to be fed in all phases of the product development, including manufacturing.

From the definition of the customer requirement up to the production planning it is necessary to apply four matrices. The first matrix takes the customer requirements as entry data and outputs the product/system design requirements. The second matrix has the design requirements as input and product characteristics as outputs. The third matrix is built using the product characteristics as entry data and outputs the manufacturing operation data. The fourth matrix uses the manufacturing operation data as input element and outputs the product quality control elements.

Figure 2 presents the typical content of the House of Quality (first matrix). Each element composes one part of the matrix.



Elements	Contents
1	Customer requirement list and relative prioritization (a What list)
2	Engineering characteristic list (a How list)
3	Engineering characteristic interrelation matrix or correlation matrix (roof)
4	Customer requirements-Engineering characteristics interrelationships
5	Customer preference chart used to assess relative competitiveness
6	Technical and cost assessment used to allocate resource on elements

Figure 2: A House of Quality structure.

3.5. DSM (Design Structure Matrix)

The Design Structure Matrix (DSM) method also known as Dependency Structure Matrix or Dependency Source Matrix, consists in modeling the relationships among several elements of a system, teams or process (Eppinger and Salminen, 2001).

A system (or project) model is generally represented graphically by a flowchart diagram or, in some other graphical forms, as Gantt or PERT (Program Evaluation and Review Technique) diagrams, as presented in Fig. 3, where the blocks represent the elements and the lines represent the type of relationship among them. The arrows indicate the influence direction of an element to the other (Yassine, 2004). The representation depicted, has three types of basic construction representing the relationship among elements: (1) Sequential (or dependent); (2) Parallel (or competitor); and (3) Connected (or interdependent) (Browning, 2002).

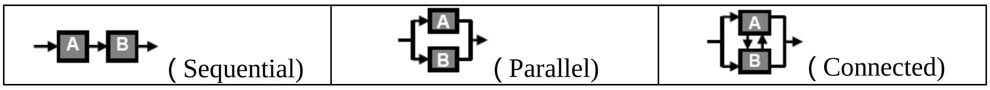


Figure 3: Graphical representation of the relationship among elements.

The description of a system can be expressed through a matrix based on DSM method, having the system elements described both in the lines and in the columns. The marks in the intermediate cells of the matrix indicate the kind of relationship existing among the elements. These marks represent that the exit of the corresponding elements provides information, material or data to the element shown in the column expressing its dependence (Browning, 2001).

In a sequential configuration, an element influences the behavior of the other in a unidirectional form, what means that an element only will process something after the end of the previous one which has done the same operation. In a parallel configuration, an element does not interact with the other. Finally, in a connected configuration, the influence or changes is bidirectional, meaning that the execution of an action by one element depends on the other, in both directions, characterizing a closed loop (Yassine, 2004) as showed in Fig. 4.

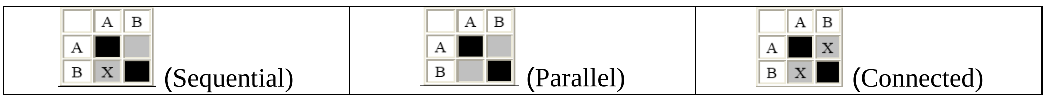


Figure 4: DSM matrix representation of relationship among elements.

The diagonal line of the matrix, that represents the intersection of the same elements, usually does not present any value, however, according to the application of the DSM it can express, in this diagonal line, the referred values of a specific attribute varying its degree in accordance with the desired parameters (Cronemyr *et al*, 2001).

3.6. TRL (Technology Readiness Level)

The Technology Readiness Level (TLR) is a methodology developed by NASA in 1980 to assist the development of its space programs. Currently its use is widely disseminated and the assessment of the level of maturity has become a mandatory item of the Department of Defense (DoD) of the U.S. government (DoD, 2005). Currently the U.S. government uses the Technology Readiness Assessment (TRA), which uses, by its turn, the TLR system as a metric and aims at assessing the degree of maturity of Critical Technology Elements (CTEs), to evaluate proposal of project development. The TRA by itself, is not a tool for risk assessment or a design review but helps decision makers to evaluate the risks involved in projects and programs by the dependence of technology with low maturity degree (Mandelbaum, 2005).

In analogy to the biological life cycle of living beings, a product has various stages throughout its existence starting up from conception, birth and childhood, youth, maturity, aging and ultimately death. Likewise is a technology life cycle (Nolte, 2005). In this model, technologies are incorporated into products in the stage of growth where there is already a reasonable stability.

The TRL maturity degree starts from 1 until 9. The lower value represents the most initial stages of technology development. Highest graduation represents technologies tested in benches, mock-ups or prototypes or, even in the field. In TRL grade 9, the technology can be considered off-the-shelf. A research carried out by the GAO (United States General Accounting Office) has found that industry applies the level of TRL 8 as the basis for implementation in their products. Conversely the Laboratory for Research of the Air Force sees a North American technology to TRL 6 as acceptable at launching a new project. Lower levels are seen of high risk (GAO, 1999). Figure 5 represents qualitatively, the risk increase with the application of a technology with low maturity degree in advanced phases of product development. Table 1 shows the nine levels of maturity used by the TRL method.

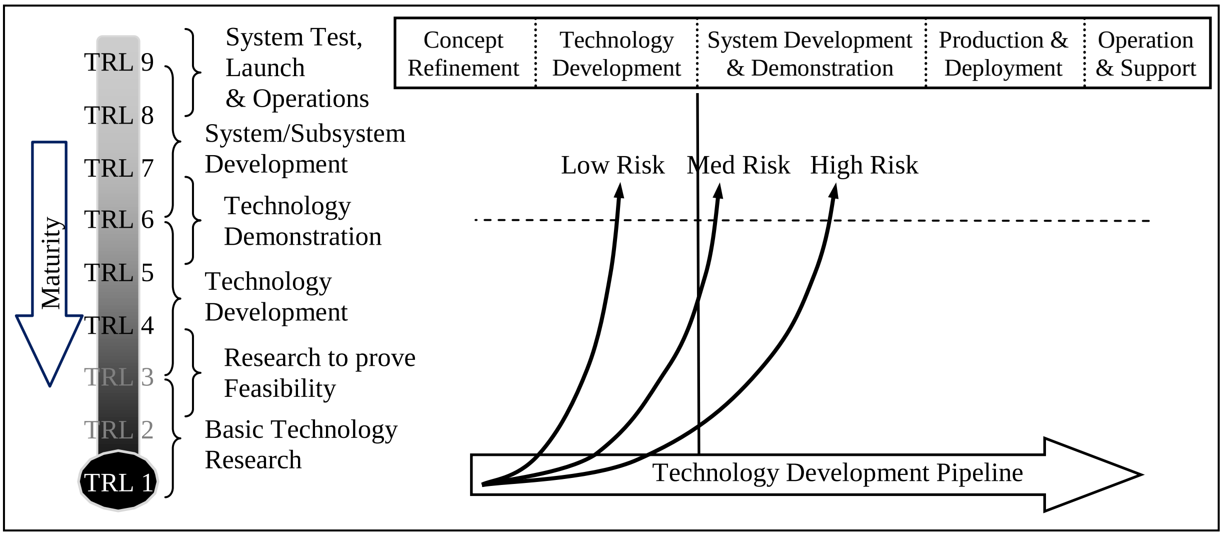


Figure 5: Technology Infusion Risk (Greenfield, 1998).

Table 1: Basic description of each TRL Level (Nolte, 2005).

Level	Basic Description
TRL 1	*Basic principles observed and reported*
TRL 2	*Technology concept and/or application formulated*
TRL 3	*Analytical and experimental critical function and/or characteristic proof-of-concept*
TRL 4	*Component and/or breadboard validation in laboratory environment*
TRL 5	*Component and/or breadboard validation in relevant environment*
TRL 6	*System/subsystem model or prototype demonstration in a relevant environment (ground or space)*
TRL 7	*System prototype demonstration in a space environment*
TRL 8	*Actual system completed and "flight qualified" through test and demonstration (ground or space)*
TRL 9	*Actual system "flight proven" through successful mission operations*

In highly complex products where a very large amount of technologies need to be incorporated, it is worthy to decide which technology should really be considered as CTE. Adopting a conservative approach and considering a lot of technologies, there is a great chance to penalize the program which is spending energy and resources as well as losing focus of what is really critical.

4. INTEGRATED METHOD PROPOSED

The method proposed herein has as main objective to assist project managers with a quantitative measure of the risks embedded in the project development by use of immature technologies in specific systems/subsystems aiming the elaboration, analysis and priorization of actions from the managers.

The proposed method consists of six stages shown in Fig. 6. These are detailed as follows: First: use of the System Engineering concepts for the deployment of the product into its subsystems/elements. Second: use of QFD concepts to establish the relationship between subsystems and requirements. Third: use of the DSM matrix to assess the relationships among all subsystems that compose the system and to define the main critical clusters considering maturity risk and impact on the other subsystems. Forth: use the results obtained from QFD and DSM to establish the CTE for the system. Fifth: assess the TRL of each CTE to define the technologies that need to be monitored by its critical importance to achieve the expected requirements or by the relationship established among all systems. Six: using the results of the previous step, carry out the monitoring of the maturity level of all critical technologies.

The main difference of the proposed method from the usual projects management process is the addition of a qualitative measurement process to assess the risk of using a specific immature technology on a subsystem. This is achieved from the use of QFD and DSM to analyze two of the most common problems in technology innovative projects, which are the main requirements compliance and how to avoid system integrations problems.

The method stages are further detailed below.

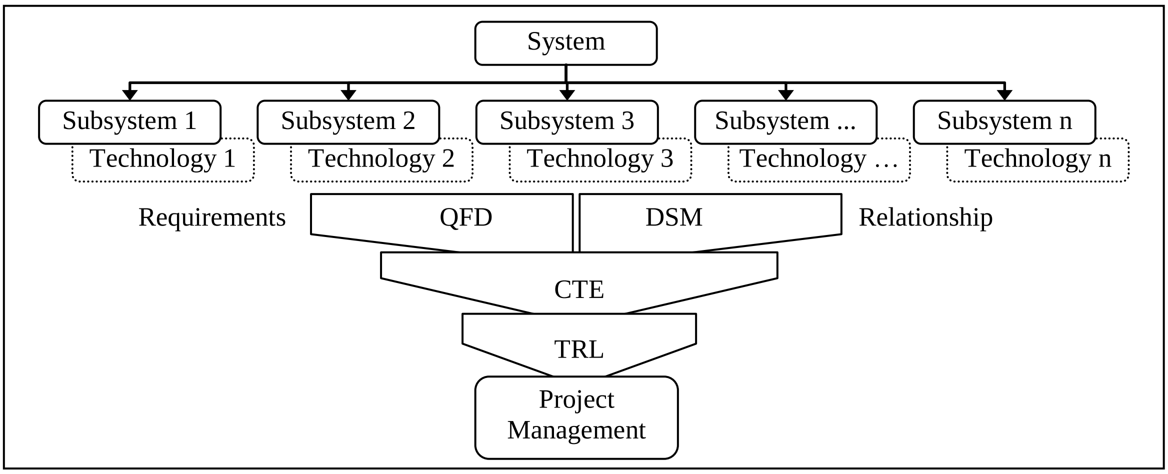


Figure 6: Workflow of the proposed Method.

Stage 1: System Deployment

One of the key stages of the proposed method, the system deployment give a good perspective of how complex is the system and how many technologies are being incorporated. A given system, which focus the development process, is deployed into subsystems or components in accordance with the criteria adopted by the Systems Engineering as presented in Fig. 7.

An important issue is to know how deep the system should be detailed. Usually it is unnecessary to reach the details of parts or components of the systems. The needed breakdown degree is that one that allows a proper view of the assembly being possible to identify one specific technology, or set of technologies, that compound the subsystem.

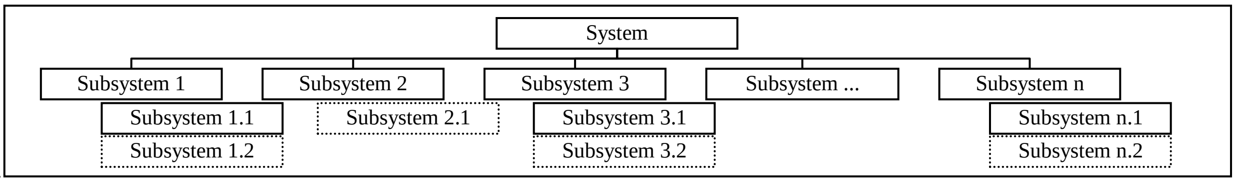


Figure 7: System breakdown into subsystems.

Stage 2: Relationship between Systems and Requirements

The customer requirement is one of the most important points in a PDP. It shows how important is a subsystem for the whole system. In this stage it is analyzed the relationship between subsystems, identified at the previous stage, that compound the system with the main requirements for customers, applying the first two matrices of QFD in order to establish the correlation between each subsystem and requirements, as shown in Fig. 8.

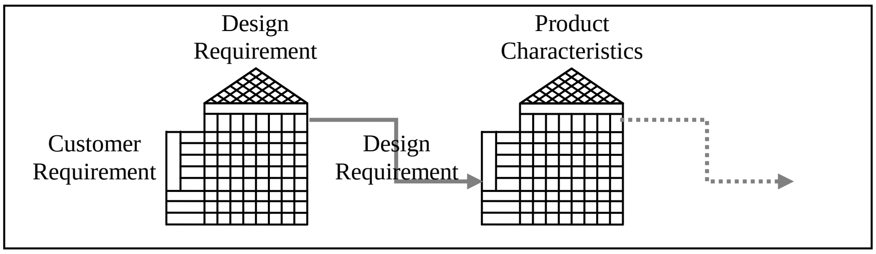


Figure 8: Two Firsts Matrices of QFD.

At the end, it is expected to grade the relative importance "*I*" of each technology, reflecting the contribution for the accomplishment of the customer needs. To set a scale of importance, it is proposed to grade 0 for the subsystems considered accessories or that do not represent a differential for customers and grade 5 for the key subsystems to meet the main requirements defined by users, leading at the end to the matrix as shown in Tab. 2.

Table 2: Subsystem importance assessment.

Subsystems	**Grade**
Subsystem 1	I1
Subsystem 2	I2
Subsystem ...	I...
Subsystem n	In

Stage 3: Subsystems Relationship Assessment

Essential to develop complex systems, the relationship analysis between subsystems can be done using the DSM matrix. The focus is to assess the potential impact that changes in certain subsystems and that can be brought to the whole system.

The proposal is to grade each existing interfaces I_{ij} between subsystems i and j, as shown in Tab. 3, in order to represent the actual importance of the relationship. Each interface should be graded form 0, which represents the absence of any kind of relationship to 5, that represents the most critical case with great degree of interface customization, information flow or energy and materials exchange as well. The diagonal line of the matrix is fulfilled with the importance grade assessed at step 2.

Table 3: Subsystems importance level assessment.

Subsystem	Subsystem 1	Subsystem 2	Subsystem 3	Subsystem ...	Subsystem n
Subsystem 1	I1	I12	I13	I...	I1n
Subsystem 2	I21	I2	I23	I...	I2n
Subsystem ...	I...	I...	I...	I...	I...
Subsystem n	In1	In2	In3	I...	In

Stage 4: Key Subsystens definition to achieve the expected requirements

Since the most important subsystem to comply with customers' requirements and the subsystems interfaces were already established up to this point, it is possible to assess the critical subsystems. These critical elements represent what should be the main focus of PDP monitoring.

The critical elements score, for each subsystem in the DSM matrix, can be measured using the Eq. (1). Here the relevance "*R*" of each "*k*" subsystem is assessed from the product among the importance levels of the subsystem "I_{kk}" and the sum of all relationship levels "I_{ki}".

$$R_k = I_{kk} \times \left(\sum_{i=1}^{n} I_{ki} - I_{kk} \right) \quad (1)$$

Stage 5: Technology maturity level assessment

One of the main objectives of this step is to identify the specific technology applied to each subsystem in order to accomplish the specified requirement. If there are several technologies ready to be used with similar performance, costs and functionality, then, the more mature should be selected. Exception occurs when a new technology can bring higher level of public recognition or competitiveness.

The second objective is to evaluate the maturity degree, according to the TRL reference model, for each technology from TRL 1 to TRL 9. At last, all information can be structured in a table showing, for each specific subsystem, the respective technology to be used and the technology maturity level.

Stage 6: Monitoring the CTE and its TRL evaluation

The result of the previous steps, finding out the CTE definition, must be used in the project development process assisting the decision makers to assess alternative technologies for critical systems and monitoring their development and maturation.

In a proactive model, the result is a preliminary risk assessment for requirements compliance.

5. RISK MANAGEMENT USING TRL METHOD - APPLICATION AND EXAMPLE

As an example of the method application, this article proposes to analyze the development process of a motorized wheelchair which must incorporate technological innovations in its final design.

Stage 1: System Deployment

The motorized wheelchair is composed by four major subsystems, namely: Chair, Seat, Control and Power as shown in Fig. 9.

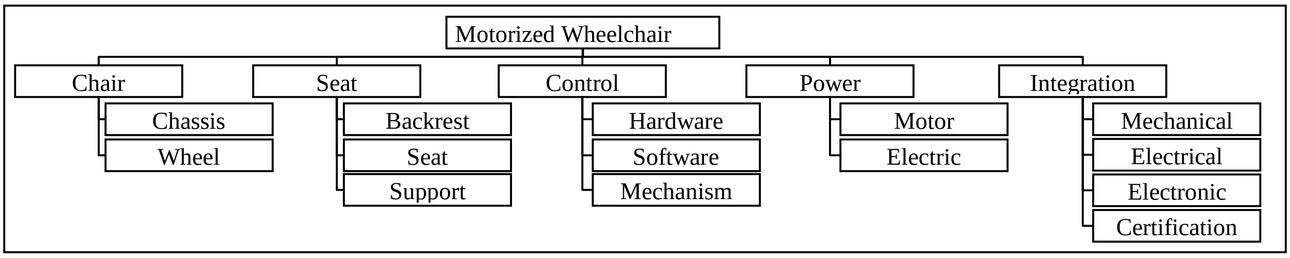


Figure 9: WBS Diagram of the project.

Stage 2: Relationship between Systems and Requirements

Interviewing customers, four items were chosen as being of major importance to the motorized wheelchair: practical use; robustness; agility and therapeutic characteristics. Figure 10 shows the breakdown structure of these items.

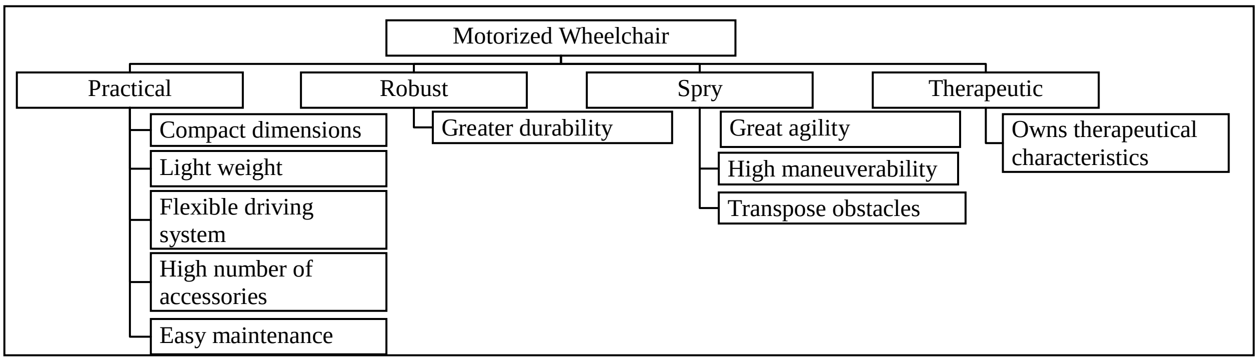


Figure 10: Breakdown of the requirements of the project.

To built the first and second matrices of QFD, it was settled the design requirements and product characteristics listed in Table 4.

Table 4: Customer Requirement, Design Requirements and Product Characteristics.

Customer requirements	Design Requirements	Product Characteristics
• Great agility	• Power	• Chassis
• High maneuverability	• Maximum diameter of spin	• Wheel
• Transpose obstacles	• Angle of attack	• Backrest
• Compact dimensions of the chairs	• Length	• Seat
• High number of accessories	• Quantity of accessories	• Support
• Owning therapeutic characteristics	• Seat and chair angle of inclination	• Hardware
• Being light	• Weight	• Software
• Easy maintenance	• Time of repair	• Mechanism
• Greater durability	• Life	• Motor
• Flexible driving system	• Number of power systems	• Electric

Once all data was identified, the house of quality could be built. The relationships between customer requirements and design requirements (Matrix 1), and between design requirement and the product characteristics (Matrix 2) are shown in Fig. 11, respectively.

	Design Requirement									
Customer Requirement	Power	Diameter of spin	Angle of attack	Length	Number of accessories	Seat and chair angle of inclination	Weight	Time of repair	Life	Number of power systems
Great agility	●						○			
High manoeuvrability		●		○						
Transpose obstacles	○		●	△			△			
Compact dimensions		△		●			△			
High number of accessories					●		△	○		
Owning therapeutical characteristics						●				
Light weight				△			●			
Easy maintenance								●		
Greater durability									●	
Flexible driving system										●

● Strong Relationship
○ Medium Relationship
△ Weak Relationship

	Design Requirement									
Product Characteristics	Power	Diameter of spin	Angle of attack	Length	Number of accessories	Seat and chair angle of inclination	Weight	Time of repair	Life	Number of power systems
Chassis			○	●			●			
Wheel			●						△	
Backrest			△		○	●	△			
Seat			△			●	△			
Support			△		●		△			
Hardware	○	○							○	
Software		○						○		
Mechanims	○						△		△	●
Motor	●		○							
Electric	●		○		○					○

● Strong Relationship
○ Medium Relationship
△ Weak Relationship

Figure 11: Synthesis of the matrix 1 and matrix 2 of the motorized wheelchair.

The analysis of the requirements expressed by the customers in relation to each subsystem that composes the wheelchair, results in a weighting degree that represents the contribution of each subsystem to fulfill the customers' requirements as shown in Table 5.

Table 5: Weighting degree requirement.

System	Grade	System	Grade
Chassis	5	Hardware	3
Wheel	1	Software	2
Backrest	2	Mechanism	2
Seat	1	Motor	2
Support	1	Electric	3

Stage 3: Subsystems Relationship Assessment

After assessed the contribution degree of each subsystem to fulfill the customer requirements, an assessment is made about the contribution degree of each subsystem for the set as a whole. In this case the DSM matrix was built to express the weighting degree of each interface among the subsystems, if any, as presented in Fig. 12.

Subsystem	Chassis	Wheel	Backrest	Seat	Support	Hardware	Software	Mechanism	Motor	Electric
Chassis	5	2	3	4	4	2		3	5	1
Wheel	2	1						2	5	
Backrest	3		2	4	2					
Seat	4		4	1	2					
Support	4		2	2	1	2		2		
Hardware	2				2	3	5	4	4	5
Software						5	1	5	5	4
Mechanism	3	2			2	4	5	2	4	5
Motor	5	5				4	5	4	2	5
Electric	1					5	4	5	5	3

Figure 12: Synthesis of the matrix 1 and matrix 2 of the motorized wheelchair.

Stage 4: Key Subsystems definition to achieve the expected requirements

Once both analysis were accomplished: the requirements fulfillment obtained through the QFD and the relationship between the subsystems evaluated using DSM, the next step is the evaluation of both criteria together. The result (calculation of the arithmetical average) express the relative importance of each subsystem as expressed in Table 6.

Table 6: Critical Technology Elements of new Motorized Wheelchair.

System	Grade (QFD)	Grade (DSM)	Results
Chassis	5	120	5
Wheel	1	9	1
Backrest	2	18	2
Seat	1	10	1
Support	1	12	1

System	Grade (QFD)	Grade (DSM)	Results
Hardware	3	66	3
Software	2	19	2
Mechanism	2	50	2
Motor	2	56	3
Electric	3	60	3

Stage 5: Technology maturity level assessment

The proposed wheelchair is, in its essence, a system with innovative concepts, however, part of the subsystems is based on mature and well established technologies, which reduces the risk of the development process, according to Table 7. An analysis on the degree of maturity of each technologies being used help to assess what critical points should be monitored.

Table 7: Applied technology in each subsystem.

Subsystem	Technology	TRL
Chassis	Aluminum alloy	TRL 8
Wheel	Default	TRL 9
Backrest	Default	TRL 9
Seat	Default	TRL 9
Support	Default	TRL 9

Subsystem	Technology	TRL
Hardware	Customized	TRL 6
Software	Customized	TRL 6
Mechanism	Touch Screen	TRL 6
Motor	Customized	TRL 7
Electric	Default	TRL 9

Stage 6: Monitoring the CTE and its TRL evaluation

As a result, the project manager should pay attention specifically at two key points, as showed in Table 8:

- The chassis, which, despite being based on mature technologies, represents a critical function by its relevance over all subsystem performing some basic functions and integrating several subsystems that compose the wheelchair;
- The element of control (Hardware, Software and Mechanism) is the critical point for the technology development by its short maturity and high interaction degree among them.

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Table 8: Applied technology in each subsystem.

Subsystem	TRL	Results
Chassis	TRL 8	5
Wheel	TRL 9	1
Backrest	TRL 9	2
Seat	TRL 9	1
Support	TRL 9	1

Subsystem	TRL	Results
Hardware	TRL 6	3
Software	TRL 6	2
Mechanism	TRL 6	2
Motor	TRL 7	3
Electric	TRL 9	3

6. CONCLUSIONS

The method presented in this paper gather some already well appraised techniques widely employed and worldwide accepted to form a coherent and concise model to assess the technological risk represented by the decision to apply low maturity technology in a system.

In fact, the method shows to be technically suitable once its results are coherent, however, it is clear that it is necessary to further test the method in order to confirm its advantages and to correct any imperfections that can exist in its concepts.

The strongest point of the presented method is its ability to assess at once several questions as requirement compliance, level of integrations and technology maturity. It makes possible to analyze the whole system instead of proceeding several partial analyses.

As a forthcoming work, interesting results could come from the possibility to stress the method applying it in other case studies including real cases.

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